Spin density matrix elements in $\Lambda(1520)$ photoproduction

Will Levine

Carnegie Mellon University

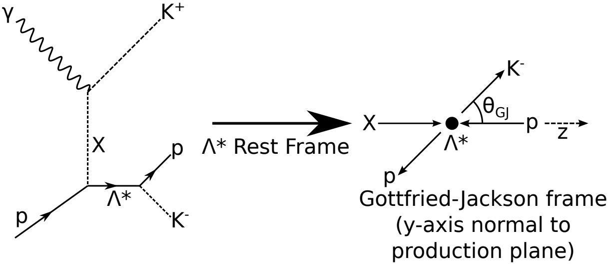
October 22, 2015

$\gamma p \to K^+\Lambda(1520)$

- $\Lambda(1520)$ is $\frac{3}{2}^-$ baryon
- Decay modes
  - $N\bar{K}$ (pK^-, $n\bar{K}^0$): 45%
  - $\Sigma\pi$ ($\Sigma^+\pi^-$, $\Sigma^0\pi^0$, $\Sigma^-\pi^+$): 42%
  - $\Lambda\pi\pi$: 10%
- Narrow resonance ($\Gamma = 15\,\mathrm{MeV}$) compared to other excited baryons

$\gamma p \to K^+\Lambda(1520)$: Polarization observables

- Polarization of $\Lambda(1520)$ expressed by spin density matrix, measured by angular distribution of decay products
- Polarization reveals information about production mechanism
- Use Gottfried-Jackson (t-channel helicity) frame



$\gamma p \to K^+\Lambda(1520)$: Polarization observables

- For decay $\frac{3}{2}^- \to \frac{1}{2}^+ 0^-$ with unpolarized target, unpolarized beam, parity-conserving production and decay: seven independent observables:

$$\begin{pmatrix} \frac{1}{2}-\rho_{\frac{1}{2}\frac{1}{2}} & \mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}})+i\mathrm{Im}(\rho_{\frac{3}{2}\frac{1}{2}}) & \mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}})+i\mathrm{Im}(\rho_{\frac{3}{2}-\frac{1}{2}}) & i\mathrm{Im}(\rho_{\frac{3}{2}-\frac{3}{2}}) \\ & \rho_{\frac{1}{2}\frac{1}{2}} & i\mathrm{Im}(\rho_{\frac{1}{2}-\frac{1}{2}}) & \mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}})-i\mathrm{Im}(\rho_{\frac{3}{2}-\frac{1}{2}}) \\ & & \rho_{\frac{1}{2}\frac{1}{2}} & -\mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}})+i\mathrm{Im}(\rho_{\frac{3}{2}\frac{1}{2}}) \\ & & & \frac{1}{2}-\rho_{\frac{1}{2}\frac{1}{2}} \end{pmatrix}$$

- Only three of these observables are measureable in decay distribution:

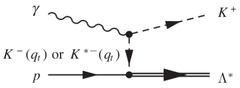
$$W(\theta,\phi)=\frac{3}{4\pi}\left\{\left(\frac{1}{3}+\cos^2\theta\right)\rho_{\frac{1}{2}\frac{1}{2}}+\sin^2\theta\left(\frac{1}{2}-\rho_{\frac{1}{2}\frac{1}{2}}\right)-\frac{1}{\sqrt{3}}\sin 2\theta\cos\phi\,\mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}})-\frac{1}{\sqrt{3}}\sin^2\theta\cos 2\phi\,\mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}})\right\}$$

Jackson, High Energy Physics, Les Houches 1965

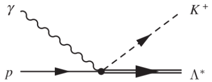
- Can generalize to case of polarized photon beam
  - Unpolarized beam: can measure 3 independent observables
  - Linearly polarized beam: 6 additional observables
  - Circularly polarized beam: 2 additional observables

Possible production mechanisms

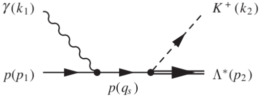
- t-channel
  - K exchange
    - Pure scalar meson exchange implies $\rho_{\frac{1}{2}\frac{1}{2}} = \frac{1}{2}$, all other $\rho = 0$ (in GJ frame)
  - K^* exchange



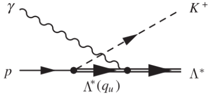
- contact term
  - Needed to preserve gauge invariance
  - Absent for photoproduction off neutron
  - Contact term dominance could explain suppressed cross-section off neutron LEPS, PRL 103, 012001 (2009)



- s-channel
  - Prediction of $N^* \to K\Lambda(1520)$ decays from $N^*(2120)\frac{3}{2}^-$ (formerly called $N^*(2080)$), missing $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states Capstick and Roberts, PRD 58, 074011 (1998)



- u-channel

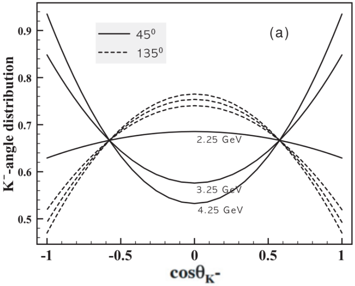


Model prediction

- Nam and Kao predict decay angular distributions as function of production angle and energy

  PRC 81, 055206 (2010)

- Model includes:
  - Reggeized t-channel (K and K^*) exchange
  - contact term
  - s-channel (ground-state N and $N^*(2120)\ \frac{3}{2}^-$) exchange
  - u-channel (ground-state Λ) exchange

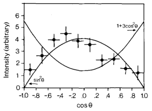


Previous measurements of decay distributions

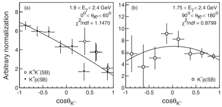
- LAMP2 (Daresbury): $E_\gamma = 2.8 - 4.8$ GeV
- LEPS: $E_\gamma = 1.75 - 2.4$ GeV, 2 angular bins
- SAPHIR: 4 bins from $E_\gamma = 1.69 - 2.65$ GeV
- All previous results averaged over wide energy bins, coarse (or no) binning in production angle

Barber et al (LAMP2), Z. Physik C 7, 17-20 (1980)

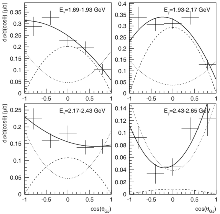
ϱ_{33}	ϱ_{11}	$\mathrm{Re}\varrho_{31}$	$\mathrm{Re}\varrho_{3-1}$
0.38 ± 0.05	0.12 ± 0.20	-0.10 ± 0.15	-0.03 ± 0.15



LEPS, PRL 103, 012001 (2009)

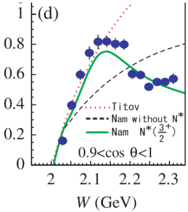


SAPHIR, Eur Phys J A 47, 47 (2011)

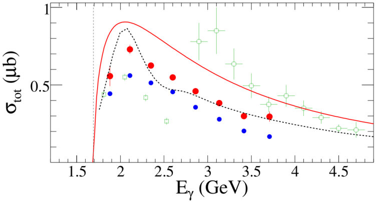


$\Lambda(1520)$ cross-section bump

- Bump in $\Lambda(1520)$ differential cross-section at $\sqrt{s} = 2.1\,\mathrm{GeV}$
- Origin unknown
  - Resonance?
  - Other?



LEPS, PRL 104, 172001

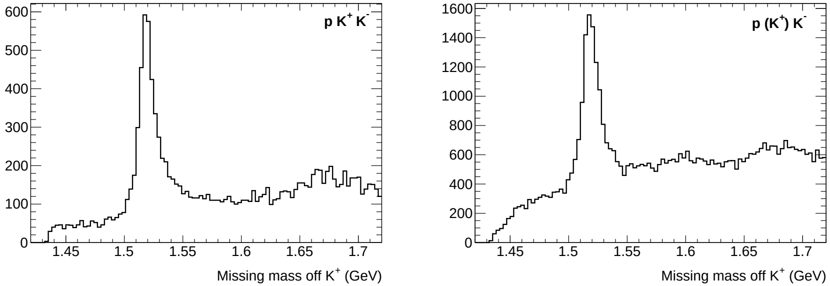


CLAS, PRC 88, 045201

Analysis overview

- g11a dataset (unpolarized)
- $\Lambda(1520) \to pK^-$ decay mode (pK^+K^- final state)
- Three independent topologies
  - pK^+K^-: minimal background
  - $pK^+(K^-)$: good statistics, good acceptance
  - $p(K^+)K^-$: access to forward production angles
  - Check systematics between channels
- Bin in 60 MeV wide $\sqrt{s}$ bins (30 MeV for pK^+K^-)
- Fiducial, timing/PID cuts
- Kinematic fit with confidence level cut
  - $\gamma p \to K^+K^-p$: 4C fit, 5% confidence level cut
  - 2-track topologies: 1C fit, 10% confidence level cut
- Cut out $IM(K^+K^-) < 1040$ MeV to remove ϕ photoproduction

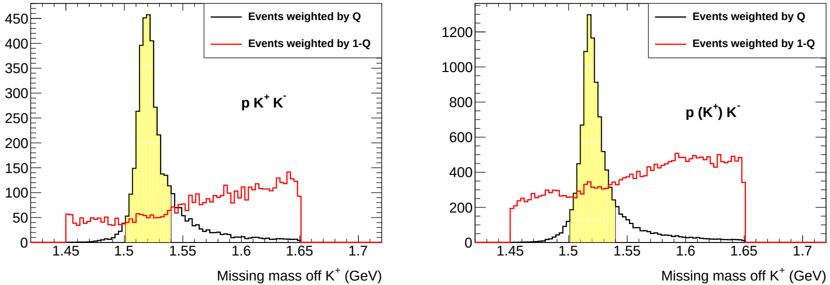
Background



$\sqrt{s} = 2340 - 2400\,\mathrm{MeV}$, after kinematic fit, all cuts

- Need to separate $\Lambda(1520)$ events from non-$\Lambda(1520)$ pK^+K^- events
- Use Q-value method
  - Event-based method, assigns each event a probability Q of being signal-like
  - Use signal probability as weight in event-based maximum likelihood fit

Background fit results



$$\sqrt{s} = 2400 - 2460\,\mathrm{MeV}$$

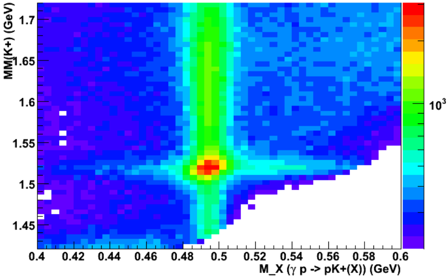
- For SDME extraction, only consider events in the center of the peak (1500-1540 MeV).

Background: Non-pK^- $\Lambda(1520)$ decays

In missing K^- topology $\gamma p \to pK^+(K^-)$, signal events are identified by $MM(K^+) \approx 1.520$ and $MM \approx m_K$.

- Non-pK^- decay modes of $\Lambda(1520)$ can mimic this signal exactly:
  - $K^+\Lambda(1520) \to K^+\Sigma^+\pi^- \to K^+p(\pi^-\pi^0)$: 7% branching fraction
  - $K^+\Lambda(1520) \to K^+\Sigma^0\pi^0 \to K^+\pi^0\Lambda\gamma \to K^+p(\pi^-\pi^0\gamma)$: 7% branching fraction
  - $K^+\Lambda(1520) \to K^+\Lambda\pi\pi \to K^+p(\pi^-\pi\pi)$: 6% branching fraction
- If missing mass $\approx m_K$, these other decays will look like pK^- decays and peak at the $\Lambda(1520)$ mass

Non-pK^- $\Lambda(1520)$ decays: Data



$\sqrt{s} = 2280 - 2310\,\mathrm{MeV}$, 2-track, before kinematic fit

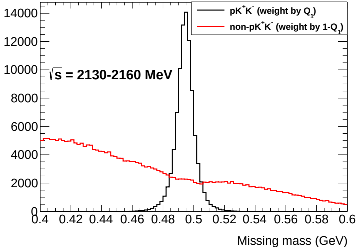
Monte Carlo indicates that background from non-pK^- $\Lambda(1520)$ 15% of size of signal

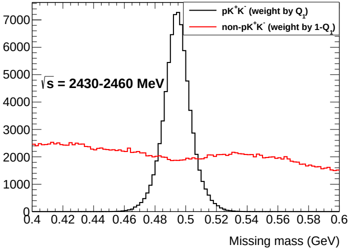
Background subtraction procedure: $\gamma p \to pK^+(K^-)$

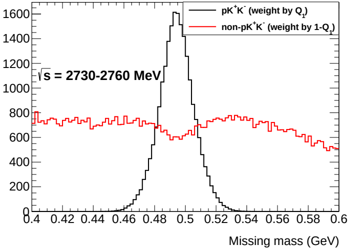
- Q-value method
  - For each event, calculate probability that given event is signal (based on mass distribution of nearest neighbors)
  - Use signal probability as weight in event-based maximum likelihood fit
- 2-stage background subtraction
  1. Q-value fit to determine probability of missing K^-: Q_1
     - Do not use kinematic fit
     - Discriminate on MM
     - Determine probability that an event pK^+K^- vs. non-pK^+K^-
  2. Q-value fit to determine probability of $\Lambda(1520)$: Q_2
     - Discriminate on $MM(K^+)$
     - Cut on kinematic fit confidence level before Q-value fit
     - Input events weighted by Q_1 results into fit 2
     - Determine probability of $K^+\Lambda(1520) \to pK^+K^-$ event as product of $Q_1 Q_2$

$\gamma p \to pK^+(K^-)$ Background subtraction: stage 1

Q-value fit, discriminate based on missing mass:

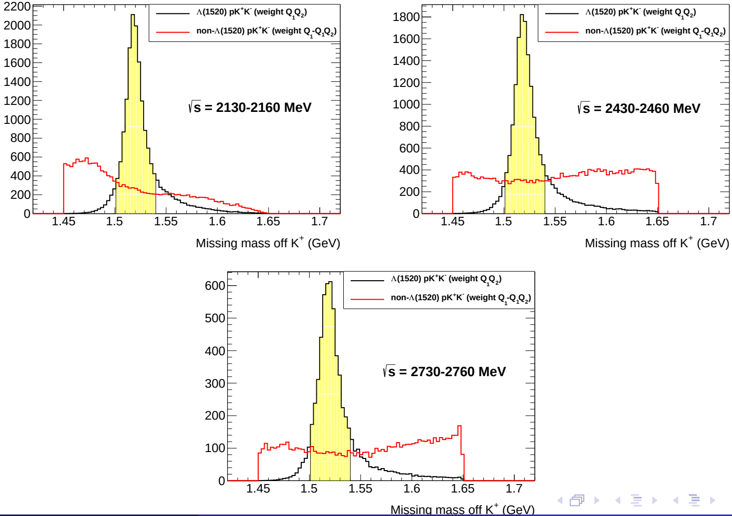




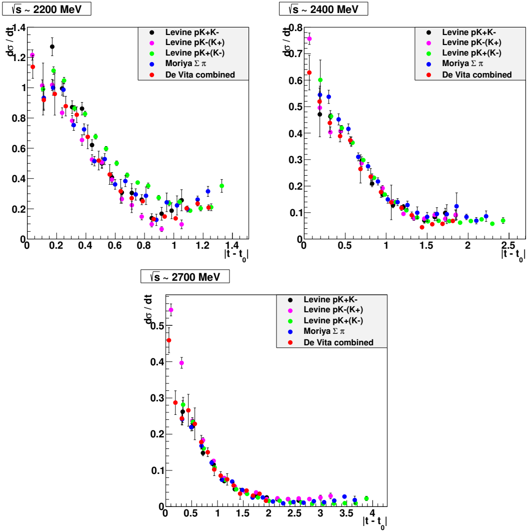


$\gamma p \to pK^+(K^-)$ Background subtraction: stage 2

Feed results of first fit into second fit (only use events that look like pK^+K^-):



Differential cross section comparison



Acceptance-aware maximum likelihood fitting

$$W(\theta,\phi) = \frac{3}{4\pi}\left\{\left(\frac{1}{3}+\cos^2\theta\right)\rho_{\frac{1}{2}\frac{1}{2}} + \sin^2\theta\left(\frac{1}{2}-\rho_{\frac{1}{2}\frac{1}{2}}\right) - \frac{1}{\sqrt{3}}\sin 2\theta\cos\phi \mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}}) - \frac{1}{\sqrt{3}}\sin^2\theta\cos 2\phi \mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}})\right\}$$

What we measure is not the true decay distribution, $W(\rho,\vec{x})$, but decay distibution times acceptance: $W(\rho,\vec{x})\eta(\vec{x})$ (ρ is the spin density matrix, $\vec{x}$ is the kinematics of the reaction, η is acceptance).

Construct a PDF for probability of detecting event with kinematics $\vec{x}$ given SDM ρ:

$$P(\rho,\vec{x}) = \frac{W(\rho,\vec{x})\eta(\vec{x})}{\int W(\rho,\vec{x}')\eta(\vec{x}')\,d\vec{x}'}$$

Denominator is easy to calculate using Monte Carlo method:

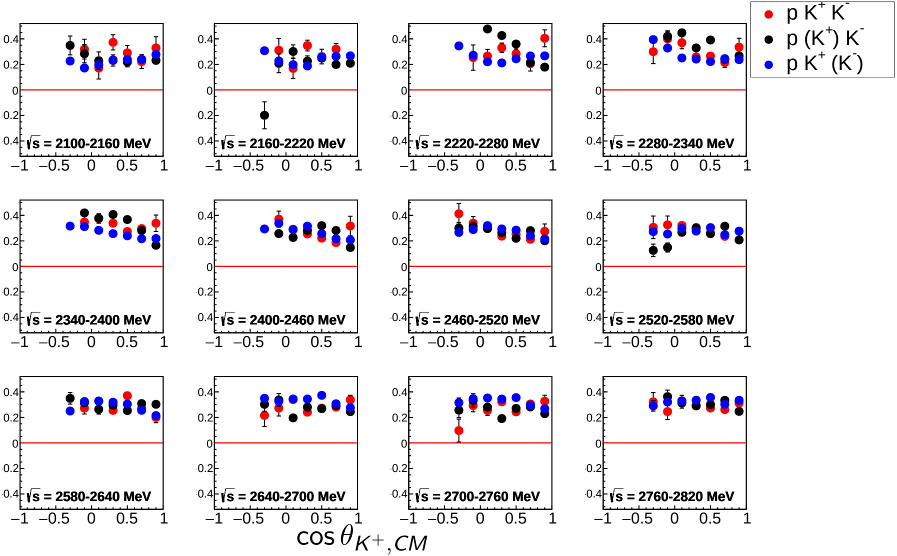
$$N(\rho) = \int W(\rho,\vec{x}')\eta(\vec{x}')\,d\vec{x}' = C\sum_{i\in accepted} W(\rho,\vec{x}_i)$$

Construct likelihood

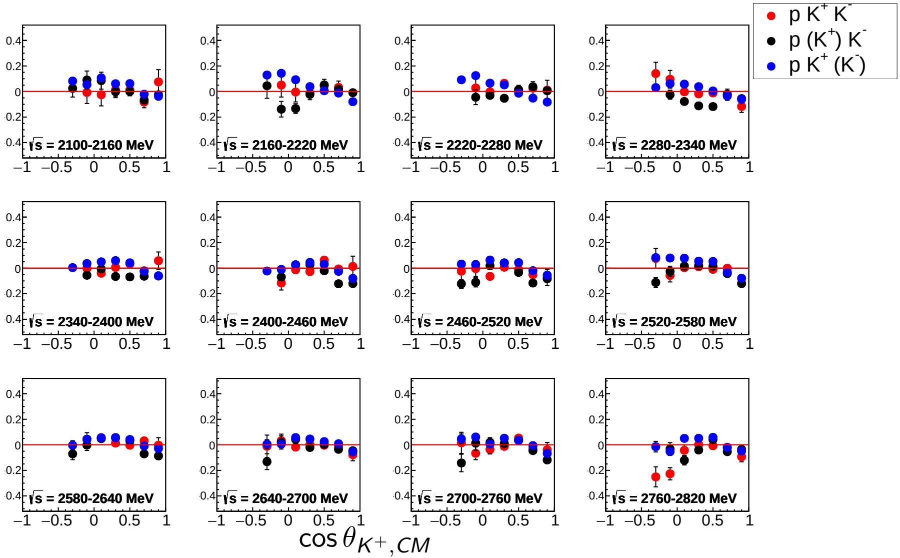
$$L \propto \prod_{i\in data}\frac{W(\rho,\vec{x}_i)}{N(\rho)}$$

Maximize L to find best values of ρ

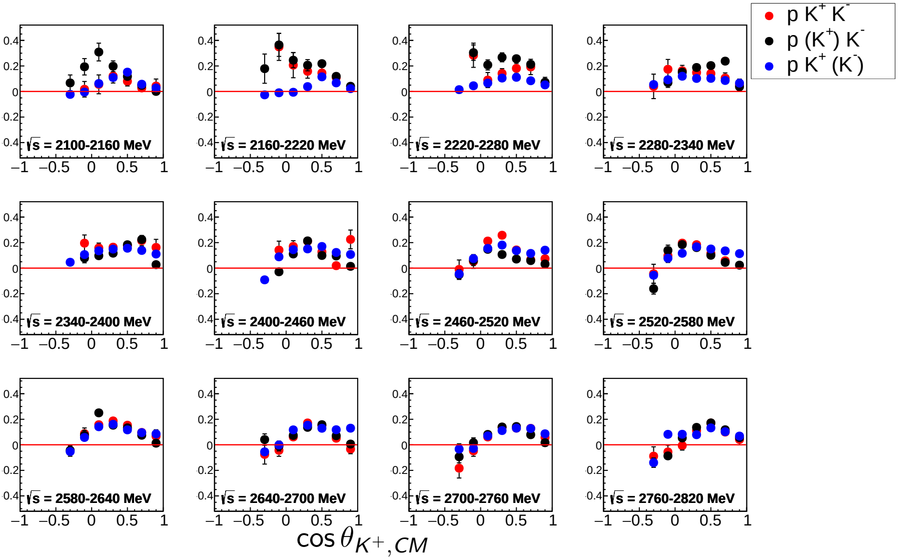
Spin density matrix: ρ_{11}



Spin density matrix: ρ_{31}



Spin density matrix: ρ_{3-1}

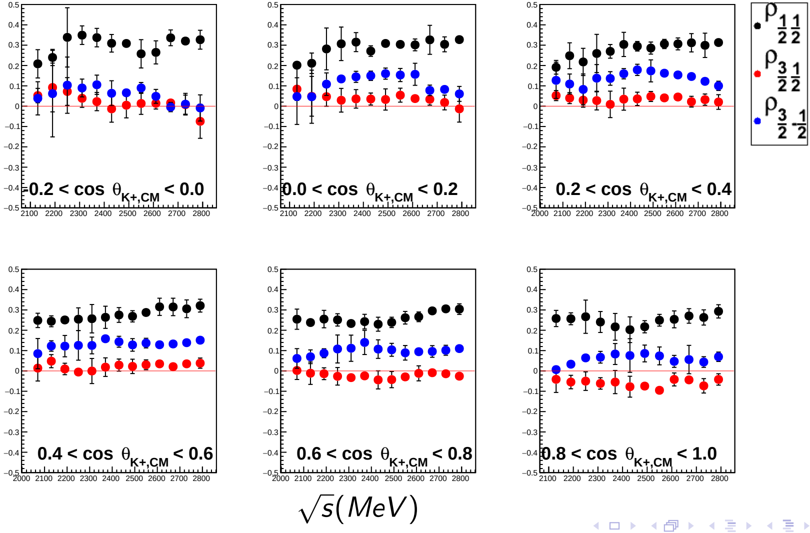


Spin density matrix elements

- Three different topologies have reasonable agreement
- Statistical errors through bootstrap method
- Estimate of systematic uncertainties from spread of values between topologies
- ρ_{31} consistent with 0 everywhere
- No strong energy dependence

Spin density matrix elements vs. E

All topologies averaged



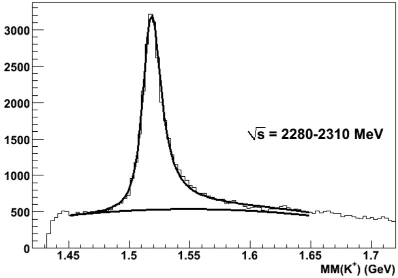
Conclusion

- Spin density matrix elements extracted for $\gamma p \rightarrow K^+\Lambda(1520)$
- Three topologies studied: pK^+K^-, $p(K^+)K^-$, $pK^+(K^-)$
- Reasonable agreement between topologies
- A few irregularities remain

Backup slides

Lineshape

Need to input functional form of MM(K^+) to do background fit:

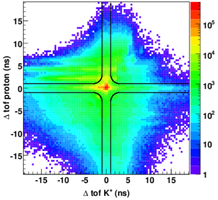


2-track, after phi cut

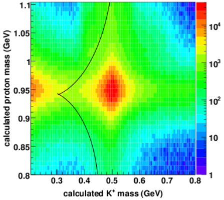
Breit-Wigner w/ mass-dependent width, convoluted with Gaussian.
Quadratic background.

Timing cuts

2-track timing cuts based on Biplab Dey's ϕ analysis ($pK+(K-)$)



(a)



B Dey thesis

Q-value method

Choose kinematic variable, M, whose distribution can be described by a sum of background and signal functions:

$$F(M, \vec{\alpha}) = S(M, \vec{\alpha}) + B(M, \vec{\alpha})$$

where $\vec{\alpha}$ is a set of unknown parameters, S is the signal distribution (e.g. Breit-Wigner), B is the background distribution (e.g. polynomial)

For each event i, find N nearest neighbors, with distance to event j as:

$$d_{ij} = \sum_k \left[\frac{\theta_k^i - \theta_k^j}{R_k} \right]^2$$

where $\vec{\theta}$ are kinematic variables other than M (e.g. $\cos\theta_{\text{production}}$, $\cos\theta_{\text{decay}}$), R_k is range of θ_k

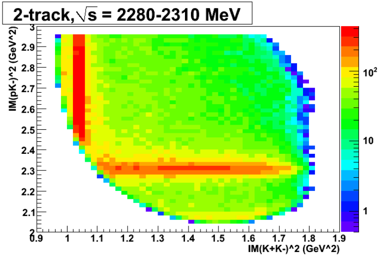
Fit M distribution of nearest neighbors to F to determine $\vec{\alpha}_i$.

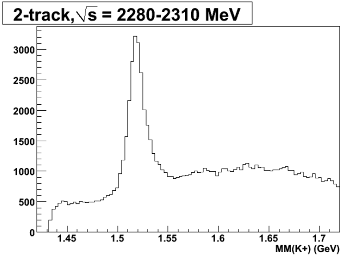
Calculate signal probability:

$$Q_i = \frac{S(M_i, \vec{\alpha_i})}{S(M_i, \vec{\alpha_i}) + B(M_i, \vec{\alpha_i})}$$

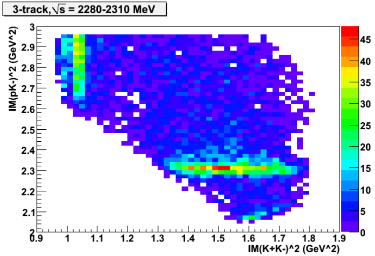
two-track vs three-track

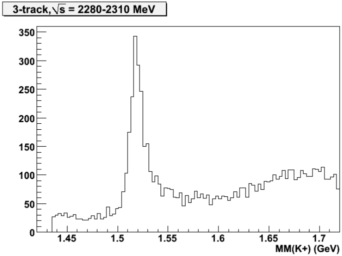
2-track: After stage 1 fit, confidence level cut:

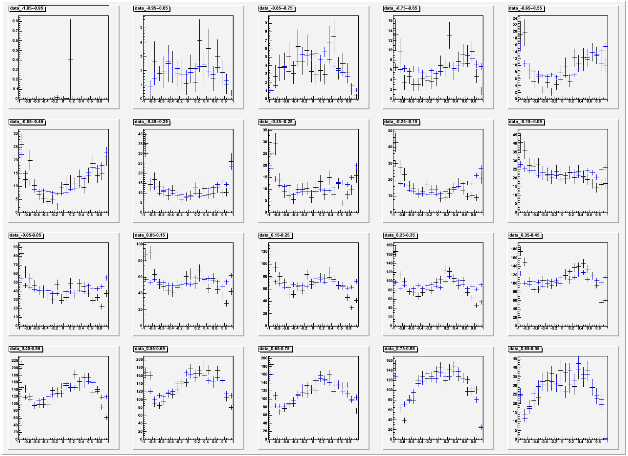




3-track: after confidence level cut:



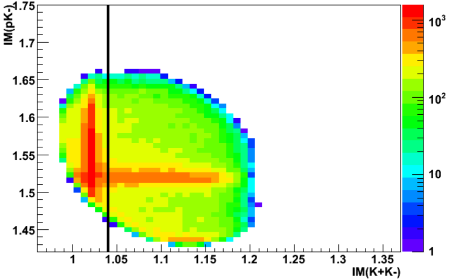




Black is data.

Blue is accepted Monte Carlo weighted by full fit to decay angular distribution.

$\Lambda(1520)/\phi$ overlap

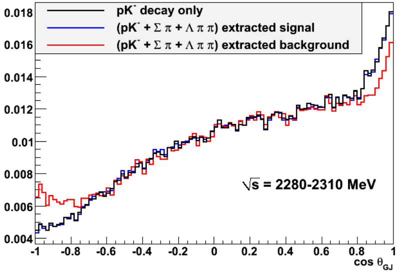


$\sqrt{s} = 2100 - 2130\,\mathrm{MeV}$, 2-track

- ϕp and $K^+\Lambda(1520)$ can decay to the same final state (K^+K^-p), overlap in phase space
- Interfering background
- Hard cut on K^+K^- mass
- No overlap at higher energies
- No overlap in 3-track (no acceptance in overlap region)

Background subtraction: MC

Combine pK^-, $\Sigma\pi$, and $\Lambda\pi\pi$ MC sample, perform background fit (stage 1):

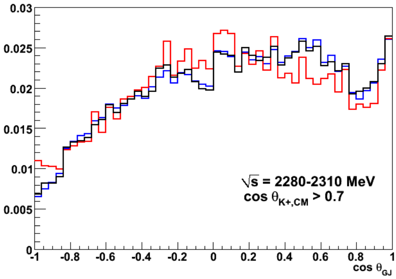


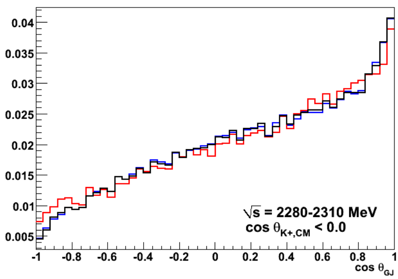
2-track, before acceptance corrections

Extracted signal decay distribution matches pK^--only distribution

Background subtraction: MC

Combine pK^-, $\Sigma\pi$, and $\Lambda\pi\pi$ MC sample, perform background fit (stage 1):



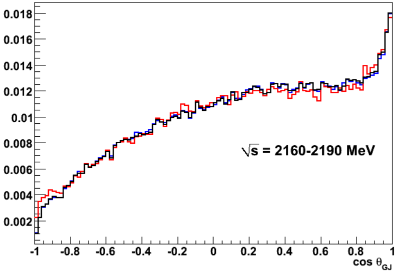


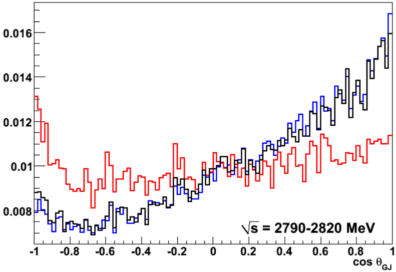
2-track, before acceptance corrections

Extracted signal decay distribution matches pK^--only distribution

Background subtraction: MC

Combine pK^-, $\Sigma\pi$, and $\Lambda\pi\pi$ MC sample, perform background fit (stage 1):

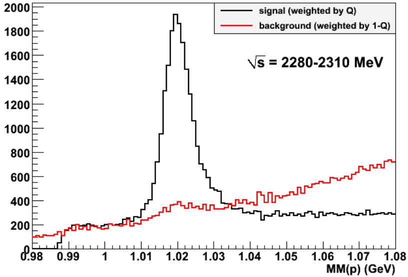




2-track, before acceptance corrections

Extracted signal decay distribution matches pK^--only distribution

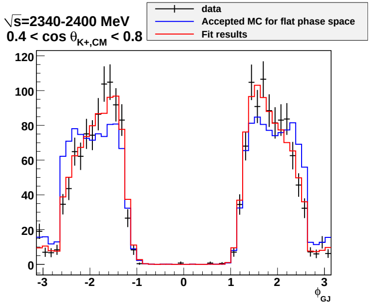
Background subtraction: data



Check that the background subtraction doesn't classify ϕ events as non-pK^+K^-

ϕ_{GJ} Decay Distributions

What about ϕ_{GJ}?
Irregular acceptance makes difficult to compare.

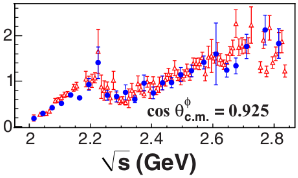


Some deviation from flat distribution

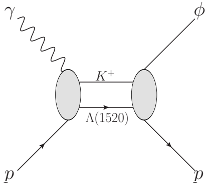
$K^+\Lambda(1520)$-ϕp coupled-channel effects

- $K^+\Lambda(1520)$ intermediate state studied in $\gamma p \to \phi p$
  - Proposed to explain bump in $\gamma p \to \phi p$ cross-section near $K\Lambda(1520)$ threshold
  - Ozaki et al, PRC 80, 035201 (2009)
  - Ryu et al, arxiv:1212.6075
- Understanding $K^+\Lambda(1520)$ production mechanism may help understanding of ϕ photoproduction

$\frac{d\sigma}{d\Omega}(\gamma p \to \phi p)$

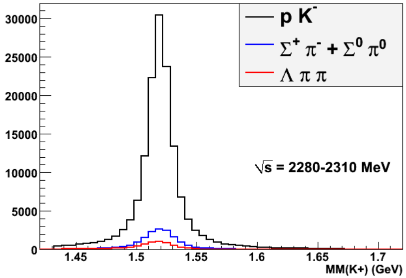


CLAS, PRC 89, 055208 (2014)



Non-pK^- $\Lambda(1520)$ decays: Monte Carlo

Simulate various $\Lambda(1520)$ decay modes (in proportion to branching ratios), apply cuts, kinematic fit to select missing K^-:



- Contamination from non-pK^- $\Lambda(1520)$ decays is 15% of true signal